OPAS Opacities

Ch.Blancard, Ph. Cossé, G. Faussurier

Presentation Overview

1. **What OPAS did**

   Some implications for the Astrophysics Community

2. **How OPAS does**

   An outside and inside view

3. **Conclusion and prospects**

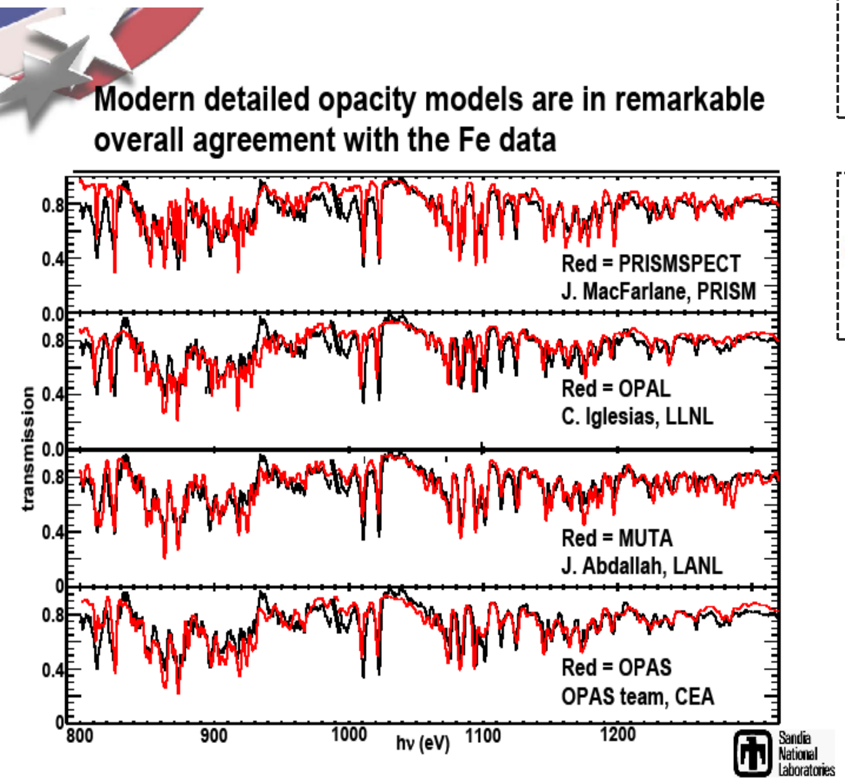
1. What OPAS did

Some implications for the Astrophysics Community

With the Sandia NL: 16 years collaboration (going on)

Towards the Radiative/Convective Boundary Zone

- The early years (2007-2010)



PRL **99**, 265002 (2007) PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2007

Iron-Plasma Transmission Measurements at Temperatures Above 150 eV

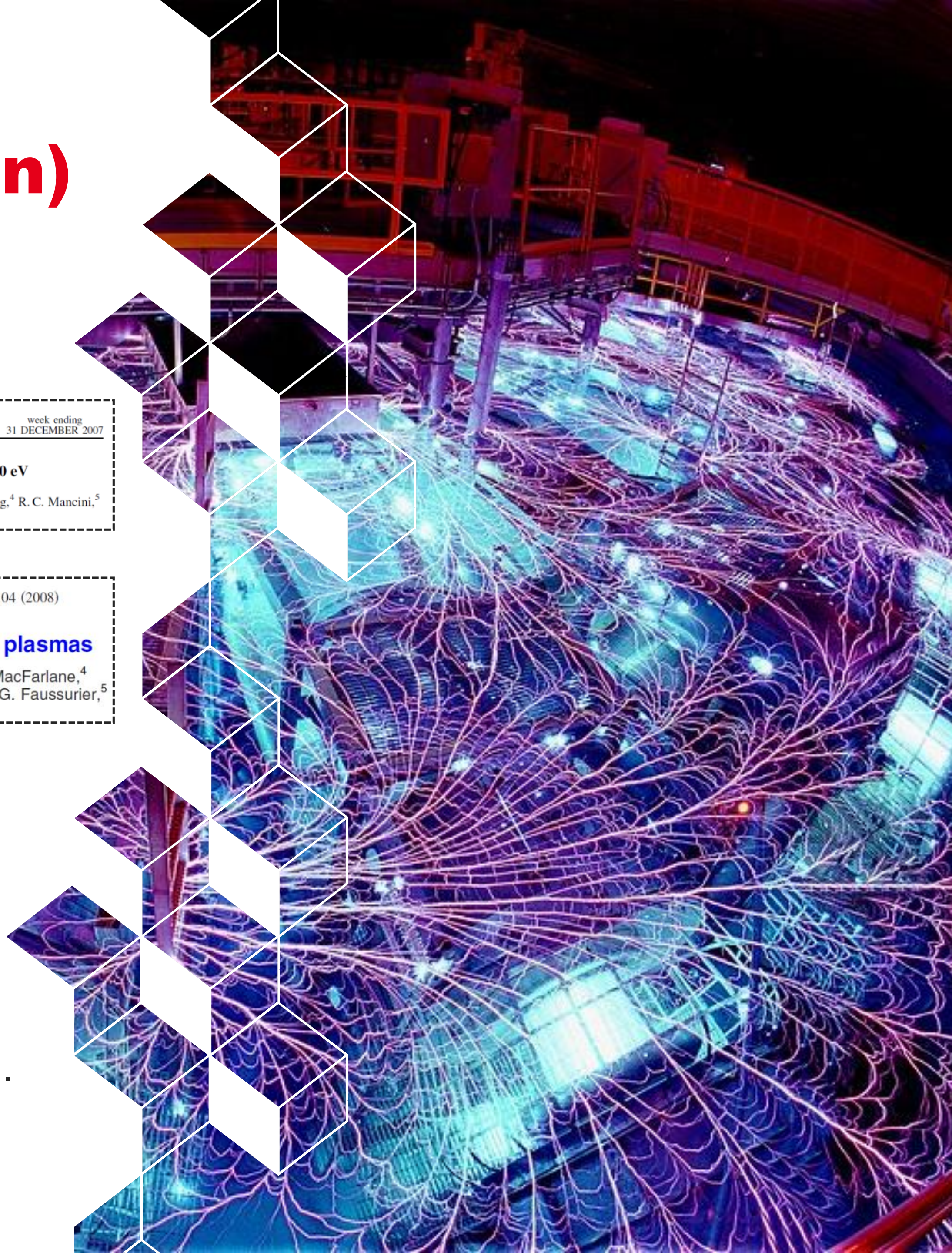
J. E. Bailey,[1] G. A. Rochau,[1] C. A. Iglesias,[2] J. Abdallah, Jr.,[3] J. J. MacFarlane,[4] I. Golovkin,[4] P. Wang,[4] R. C. Mancini,[5] P. W. Lake,[1] T. C. Moore,[6] M. Bump,[6] O. Garcia,[6] and S. Mazevet[7]

REVIEW OF SCIENTIFIC INSTRUMENTS **79**, 113104 (2008)

Diagnosis of x-ray heated Mg/Fe opacity research plasmas

J. E. Bailey,[1] G. A. Rochau,[1] R. C. Mancini,[2] C. A. Iglesias,[3] J. J. MacFarlane,[4] I. E. Golovkin,[4] J. C. Pain,[5] F. Gilleron,[5] C. Blancard,[5] Ph. Cosse,[5] G. Faussurier,[5] G. A. Chandler,[1] T. J. Nash,[1] D. S. Nielsen,[1] and P. W. Lake[1]

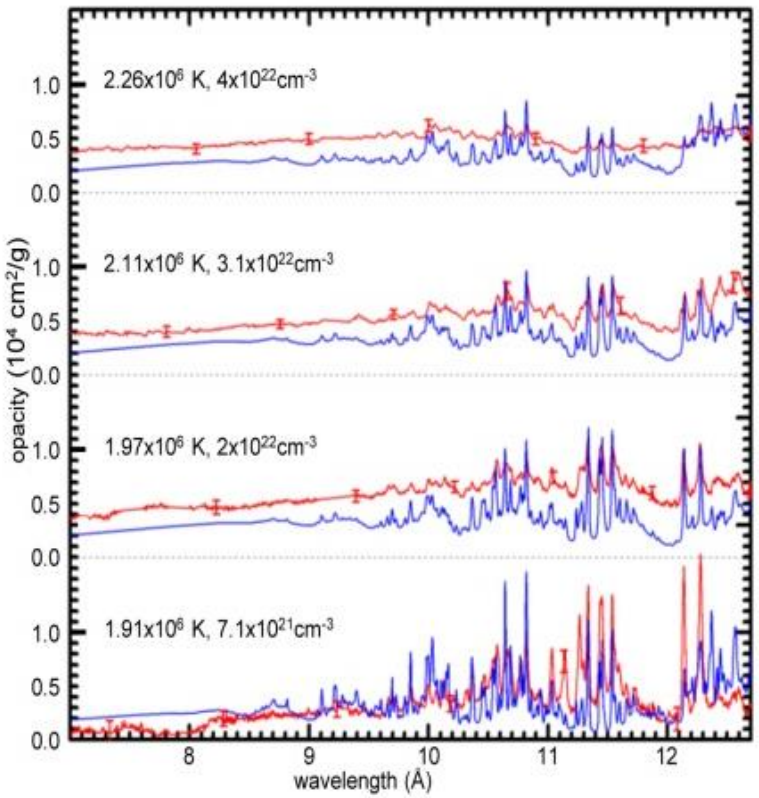
Up to 1.75×10^6 K:
remarkable agreement...



With the Sandia NL: 16 years collaboration (going on)

Towards the Radiative/Convective Boundary Zone

- The 2nd phase (2010-2015)



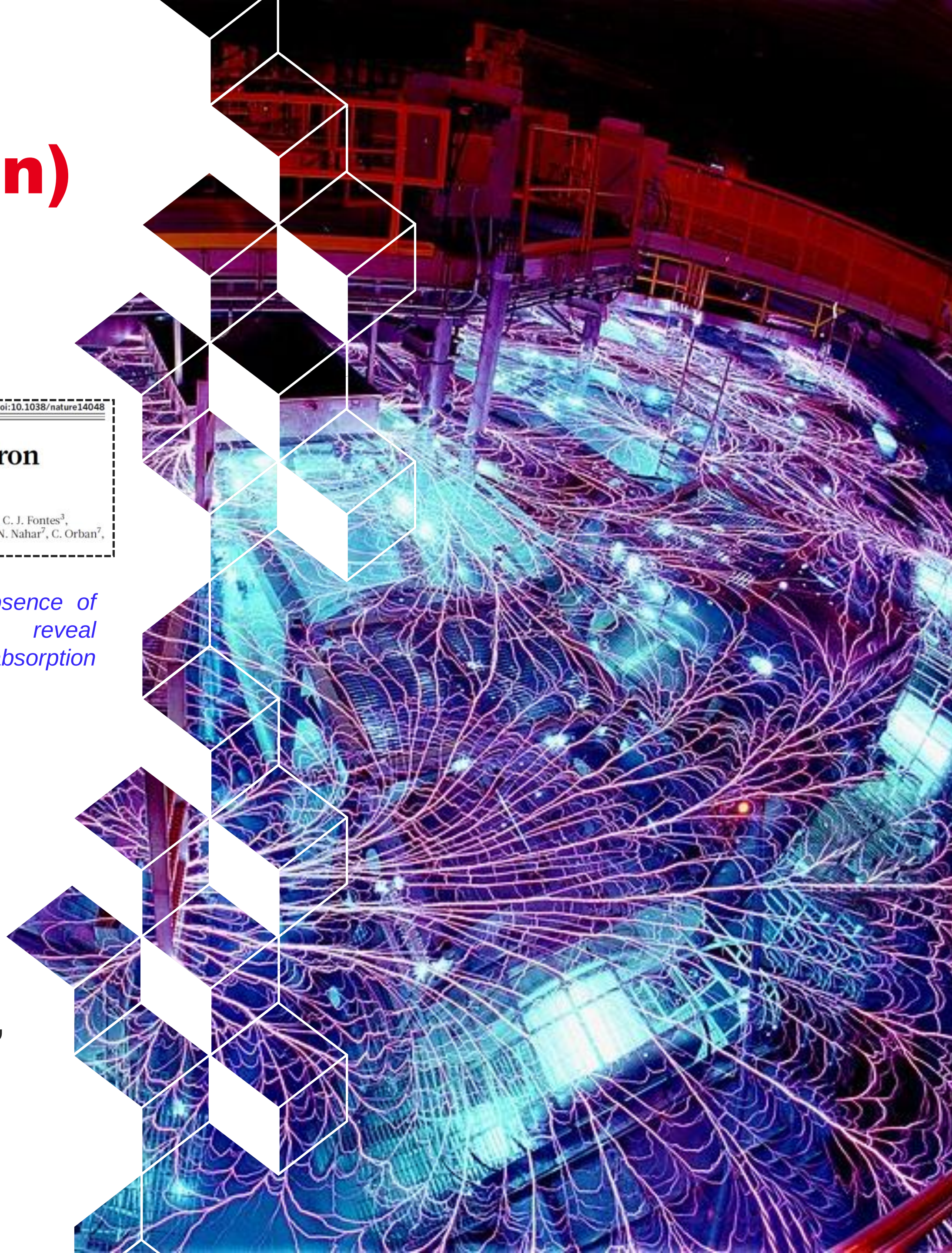
doi:10.1038/nature14048

A higher-than-predicted measurement of iron opacity at solar interior temperatures

J. E. Bailey[1], T. Nagayama[1], G. P. Loisel[1], G. A. Rochau[1], C. Blancard[2], J. Colgan[3], Ph. Cosse[2], G. Faussurier[2], C. J. Fontes[3], F. Gilleron[2], I. Golovkin[4], S. B. Hansen[1], C. A. Iglesias[5], D. P. Kilcrease[3], J. J. MacFarlane[4], R. C. Mancini[6], S. N. Nahar[7], C. Orban[7], J.-C. Pain[2], A. K. Pradhan[7], M. Sherrill[3] & B. G. Wilson[5]

"The analysis suggests that the data, in the absence of unidentified systematic experimental errors, reveal extraordinary, previously unobserved photon absorption phenomena in plasmas.", Carlos Iglesias.

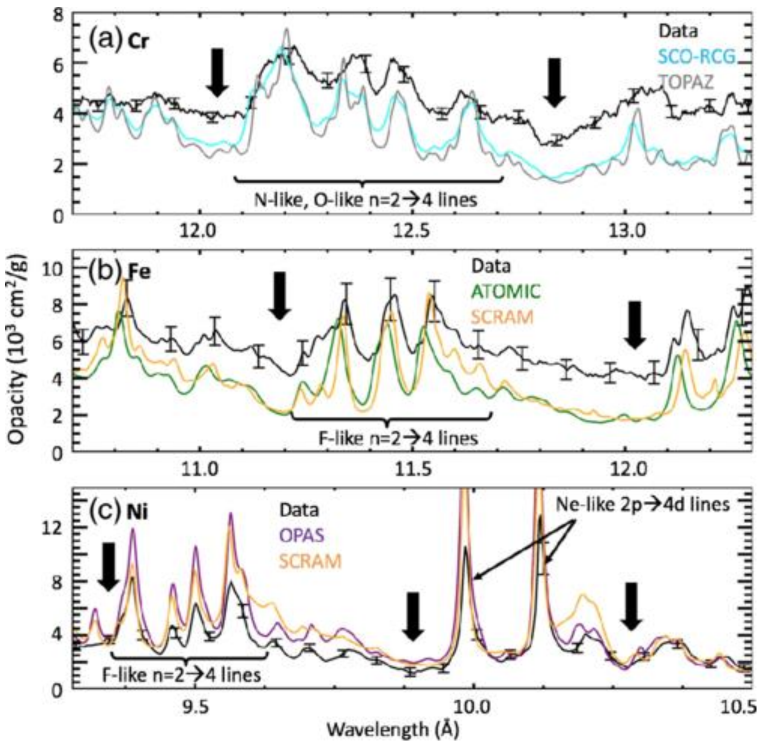
Refurbished Z-machine, questioned theories...

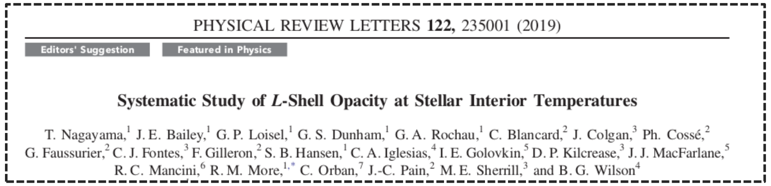


With the Sandia NL:
16 years collaboration (going on)

Towards the Radiative/Convective Boundary Zone

- The 3rd phase (2015-nowadays)



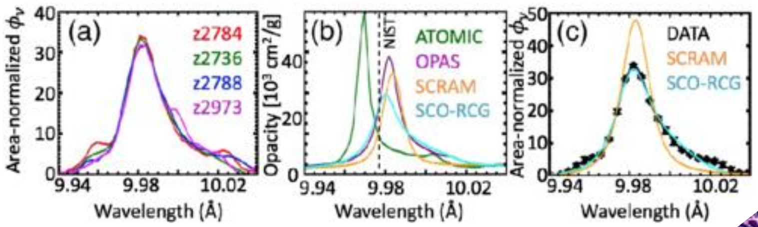


PHYSICAL REVIEW LETTERS 122, 235001 (2019)

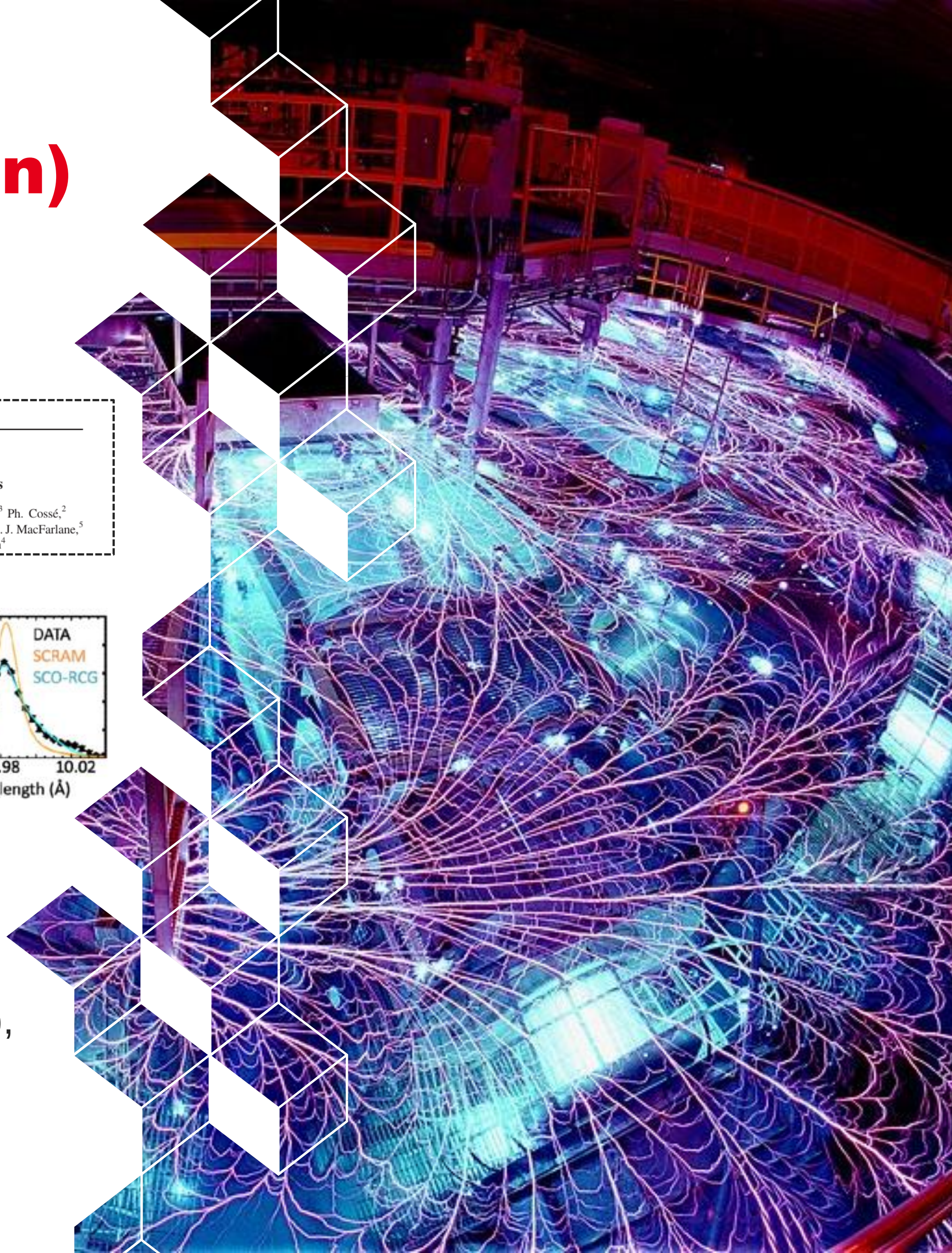
Editors' Suggestion | Featured in Physics

Systematic Study of *L*-Shell Opacity at Stellar Interior Temperatures

T. Nagayama,[1] J. E. Bailey,[1] G. P. Loisel,[1] G. S. Dunham,[1] G. A. Rochau,[1] C. Blancard,[2] J. Colgan,[3] Ph. Cossé,[2] G. Faussurier,[2] C. J. Fontes,[3] F. Gilleron,[2] S. B. Hansen,[1] C. A. Iglesias,[4] I. E. Golovkin,[5] D. P. Kilcrease,[3] J. J. MacFarlane,[5] R. C. Mancini,[6] R. M. More,[1,*] C. Orban,[7] J.-C. Pain,[2] M. E. Sherrill,[3] and B. G. Wilson[4]



New elements (including O),
new experimental setup,
new wonderings...



With the IRFU-CEA Saclay: fruitful affinities

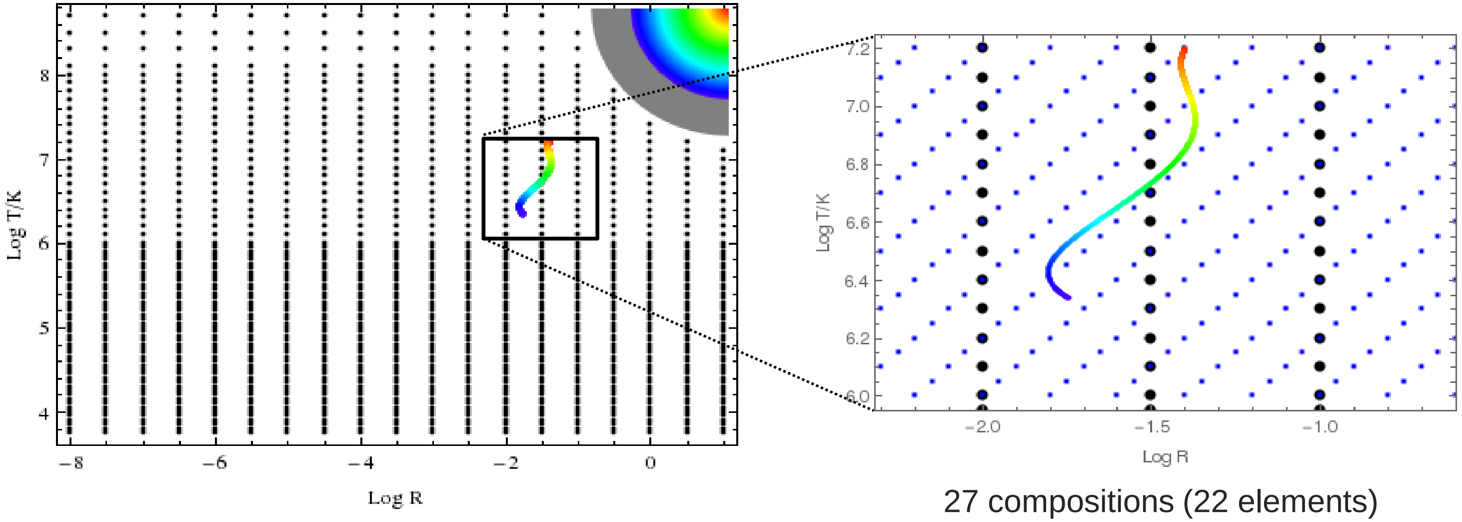
Opacity tables for the Radiative Zone of the Solar-type stars

The Astrophysical Journal Supplement Series, 220:2 (7pp), 2015 September doi:10.1088/0067-0049/220/1/2

OPACITY CALCULATIONS FOR SOLAR MIXTURES

Guillaume Mondet, Christophe Blancard, Philippe Cossé, and Gérald Faussurier
CEA, DAM, DIF, F-91297 Arpajon, France
Received 2015 April 13; accepted 2015 July 4; published 2015 August 26

OPAL (1996) OPAS (2015)



27 compositions (22 elements)

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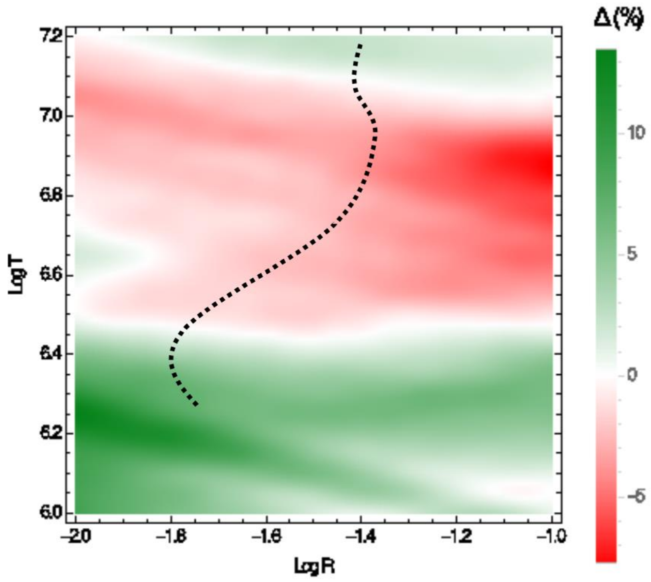
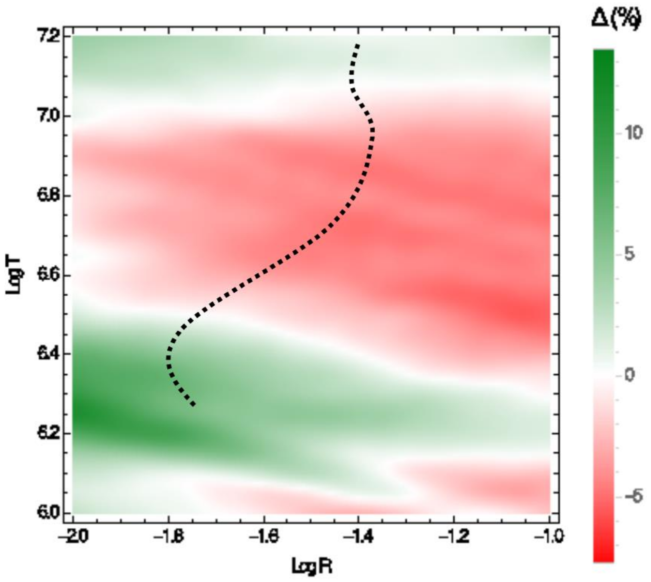
OPAS vs OP



OPAS vs OPAL



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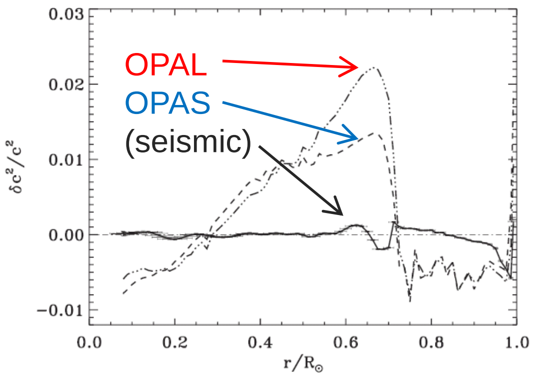
The Astrophysical Journal Letters, 813:L42 (6pp), 2015 November 10 doi:10.1088/2041-8205/813/2/L42

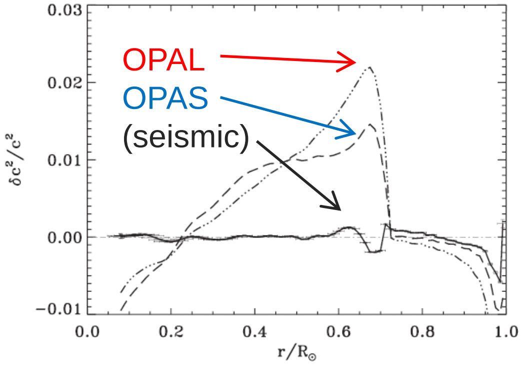
FIRST NEW SOLAR MODELS WITH OPAS OPACITY TABLES

M. Le Pennec[1], S. Turck-Chièze[1], S. Salmon[1], C. Blancard[2], P. Cossé[2], G. Faussurier[2], and G. Mondet[2]
[1] CEA/IRFU/Service d'Astrophysique, CE Saclay, F-91191 Gif sur Yvette, France
[2] CEA, DAM, DIF, F-91297 Arpajon, France
Received 2015 July 31; accepted 2015 October 15; published 2015 November 10

Code: MESA



Code: CLES



2. How OPAS does

An outside and inside view

A typical OPAS production

The (only) input:

- thermodymical conditions
- a mixture composition

The mixture opacity: $\kappa(u) = \sum_Z \mu_Z \, \kappa_Z(u)$

where μ_Z are the mixing coeff. $\left(\sum_Z \mu_Z = 1\right)$

and where the κ_Z are computed @ $\sum_Z \frac{\mu_Z}{\rho_Z} = \frac{1}{\rho}$,

under the constraints: iso-T, iso-N_e, iso-$P(\varepsilon)$

The Rosseland Mean:

$$\frac{1}{\kappa_R} = \int \frac{1}{\kappa(u)} \, f_R(u) \mathrm{d}u \, ,$$

where: $f_R(u) = \frac{15}{4\pi^4} \frac{u^4 e^{-u}}{(1-e^{-u})^2}$

The contributions:

$$\Rightarrow \frac{\partial \kappa_R}{\partial \mu_Z} = {\kappa_R}^2 \int \frac{\kappa_Z(u)}{\kappa^2(u)} \, f_R(u) \mathrm{d}u$$

$$\Rightarrow \sum_Z \mu_Z \frac{\partial \kappa_R}{\partial \mu_Z} = \kappa_R$$

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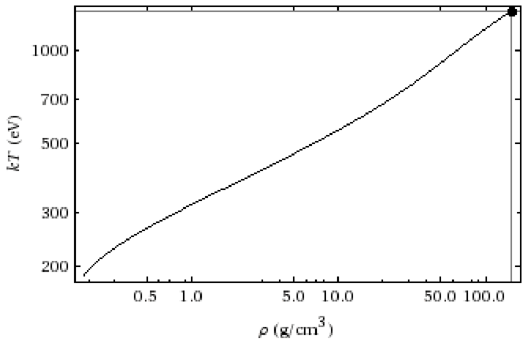

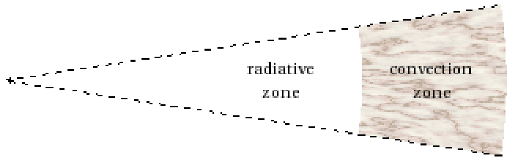

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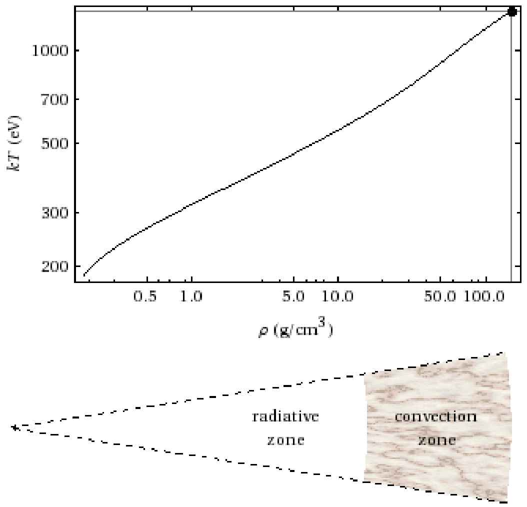

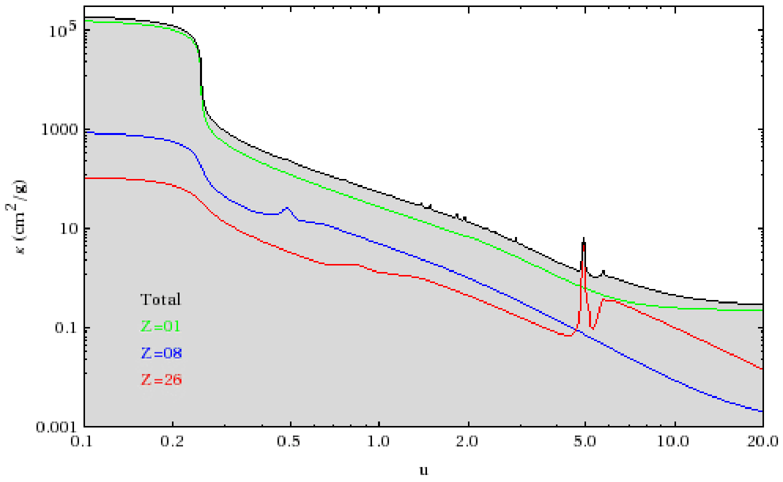

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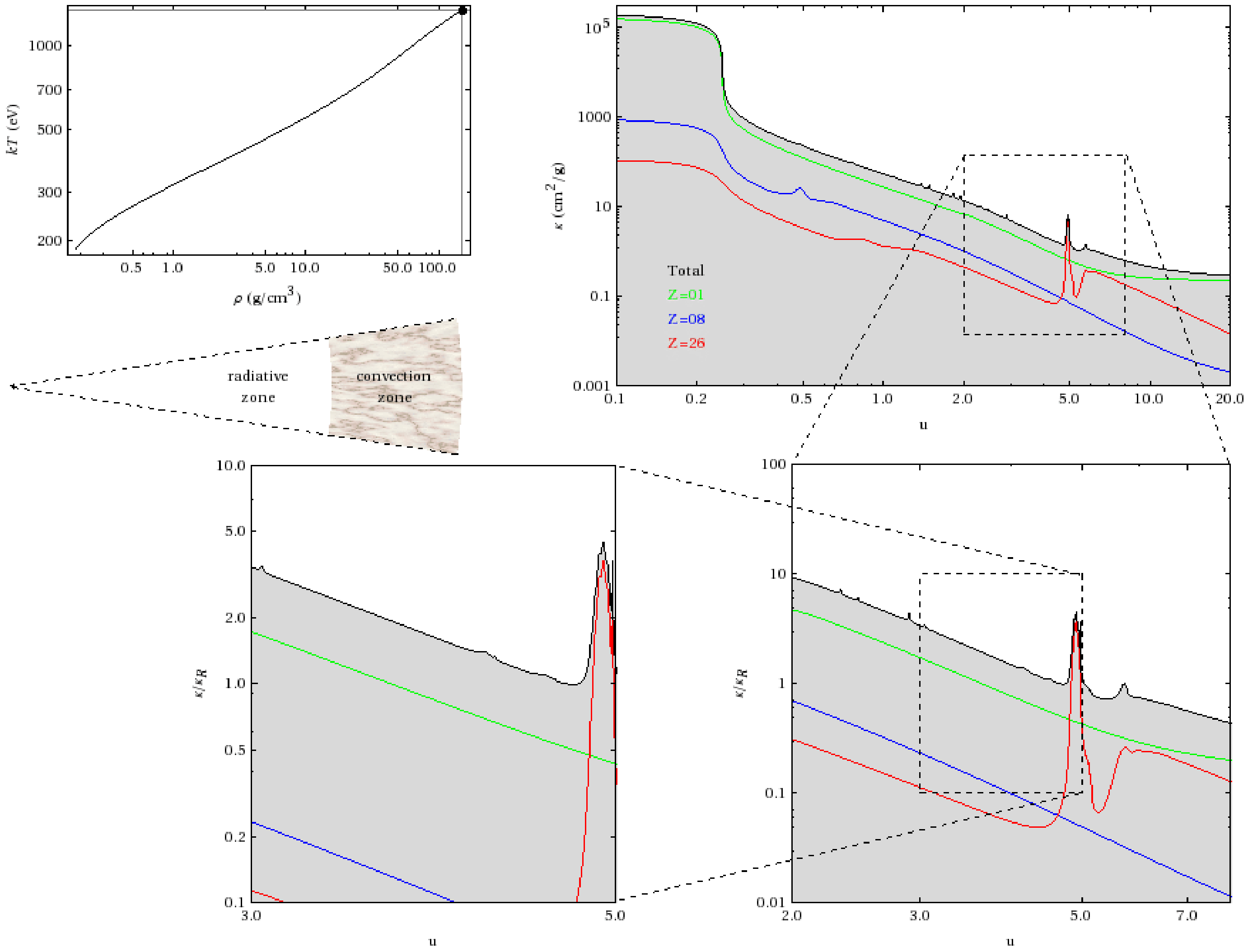

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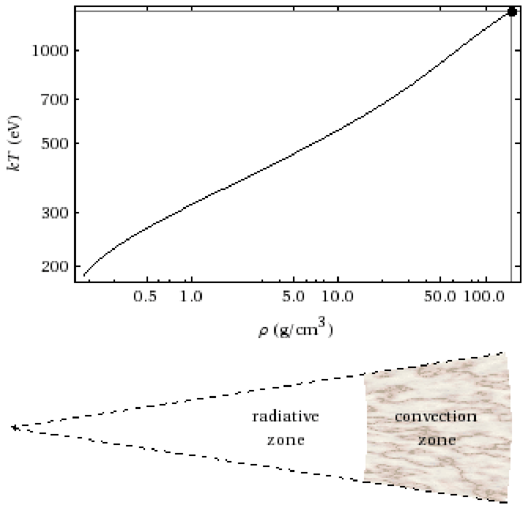

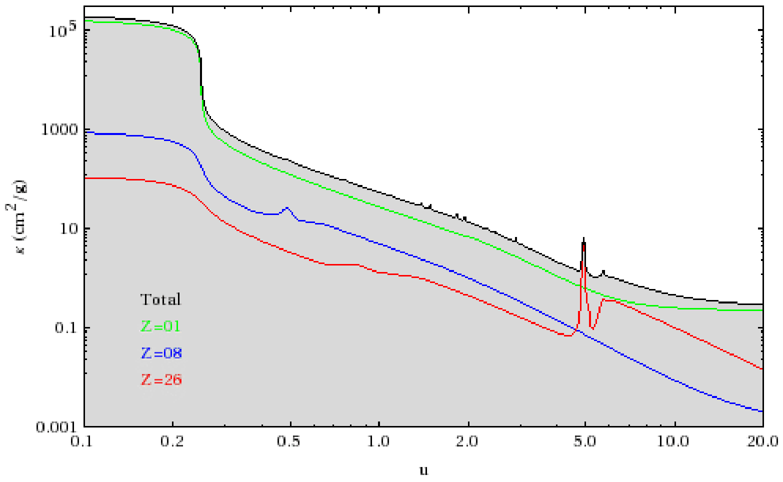

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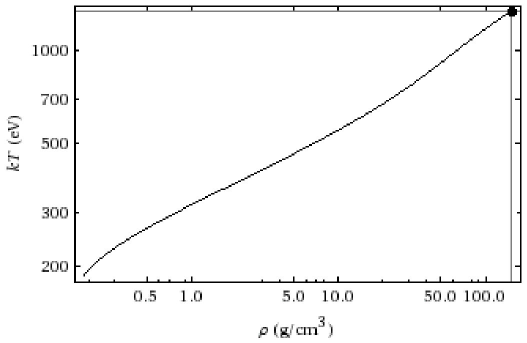

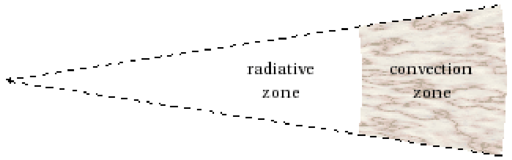

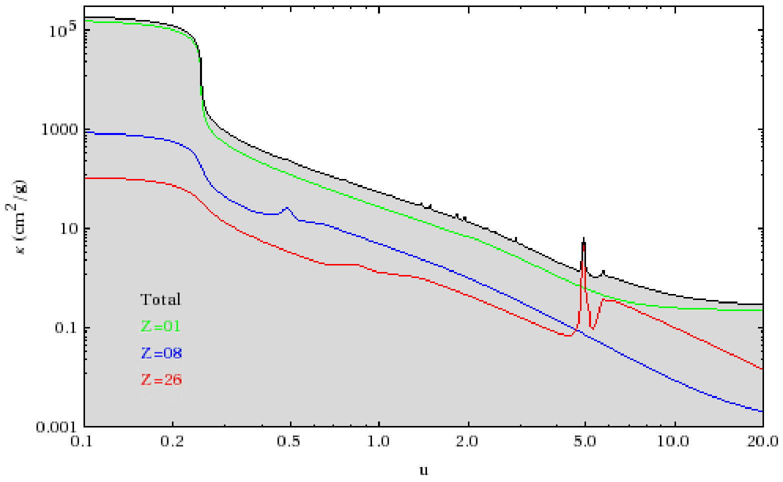

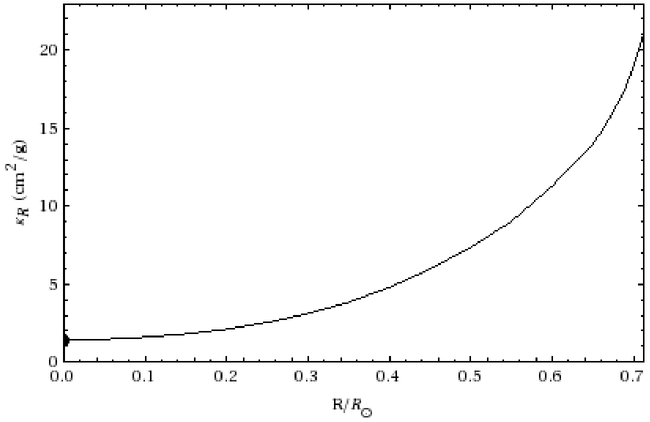

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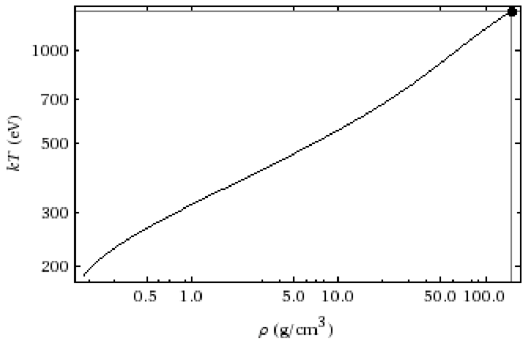
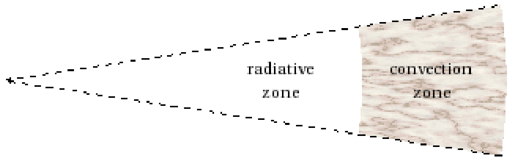
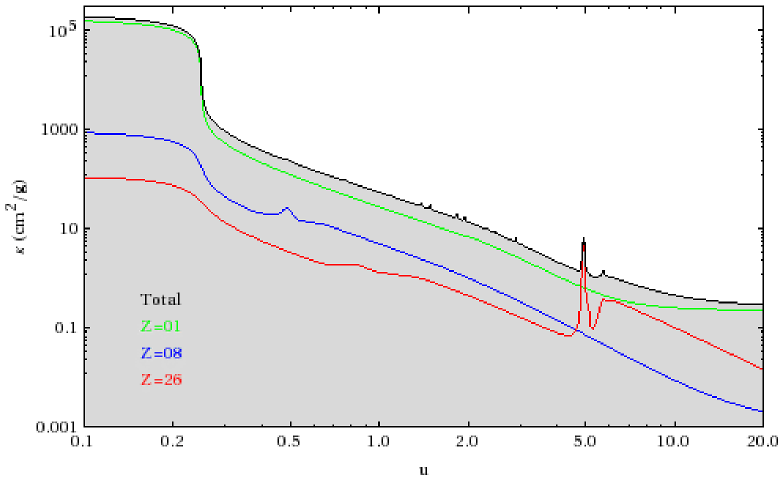
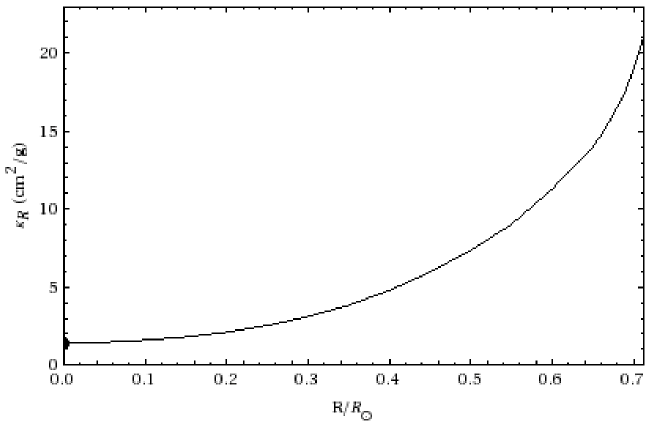
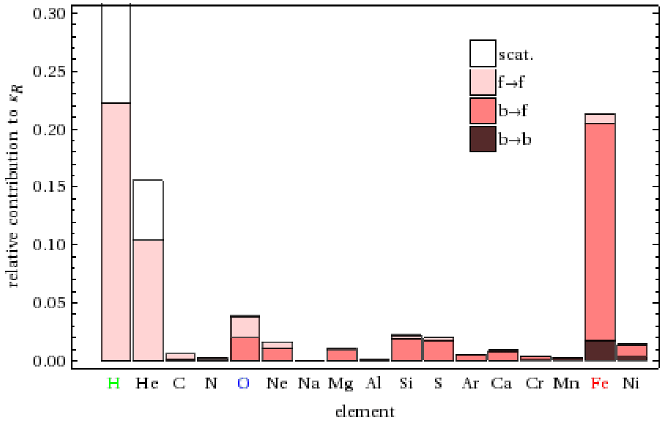










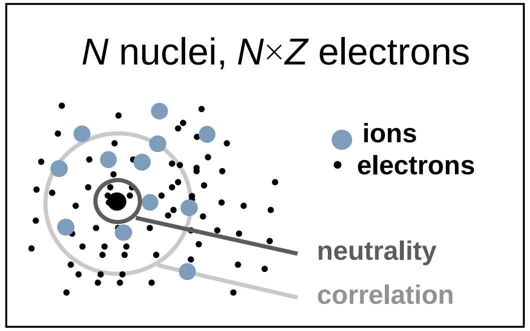
OPAS is a multi-scale atomic code, based on the thermodynamic description of plasma

Average Atom	Super-Configurations	Configurations	Atomic Levels	Atomic States

The SCAALP Model

Ab initio, variational approach

Classical ions + quantum e$^-$ (consistently processed)



Useful data for *consistent* opacities:

- Total free energy (ions+e-)
- Electronic electric conductivity
- Mean Ionization
- Subshells occupation statistics
- Ionic microfield

OPAS is a multi-scale atomic code, based on the thermodynamic description of plasma

Average Atom	**Super-Configurations**	Configurations	Atomic Levels	Atomic States

From AA statistics,
define *Super-Shells*
and their occupation range

$1s^{1.99}\ 2s^{1.85}\ 2p^{5.20}\ 3s^{0.05}\ 3p^{0.11}\ 3d^{0.20}$ ...

→ $(1s)^{0\text{-}2}\ (2s2p)^{0\text{-}8}\ (3s3p3d)^{0\text{-}2}$ ...

For each *Super-Configuration*,
optimize the electronic structure
to describe its configurations

$(1s)^2\ (2s2p)^8\ (3s3p3d)^2$ ...

⋮

$(1s)^2\ (2s2p)^4\ (3s3p3d)^1$ ...

⋮

$1s^2\ 2s^2\ 2p^6\ 3s^2$ ...

$1s^2\ 2s^2\ 2p^6\ 3s^1\ 3p^1$ ...

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⋮

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⋮

$1s^2\ 2p^4\ 3p^1$ ...

⋮

OPAS is a multi-scale atomic code, based on the thermodynamic description of plasma

Average Atom	Super-Configurations	**Configurations**	Atomic Levels	Atomic States

Get the population of every generated configuration: (~10^6)

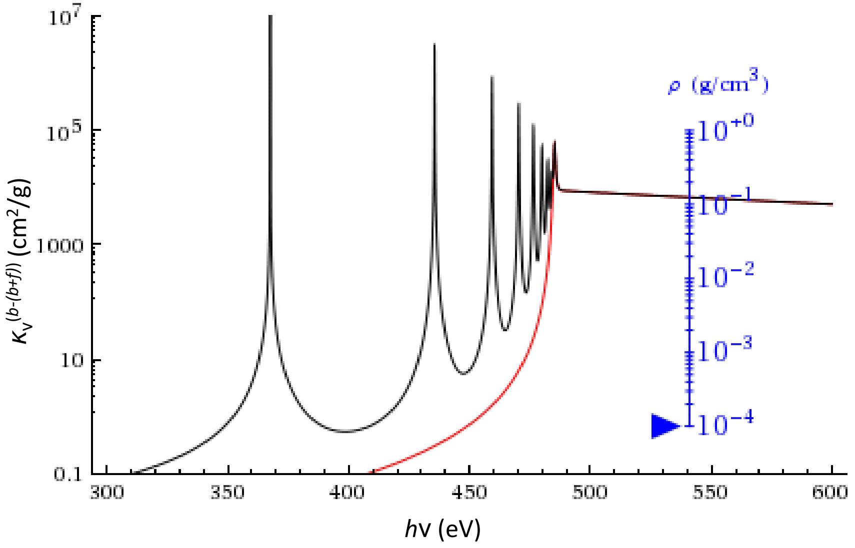
- from the Saha-Boltzmann law (LTE hypothesis)
- adjusting μ_e to retrieve the SCAALP mean Ionization value

Then, discard the most unpopulated ones. (~10^5)

The bound-free component is computed at this scale, including:

- a statistical broadening
- an Ionization Potential Shift
- ghost (almost bound) lines

C (100 eV), 1s-*xp*



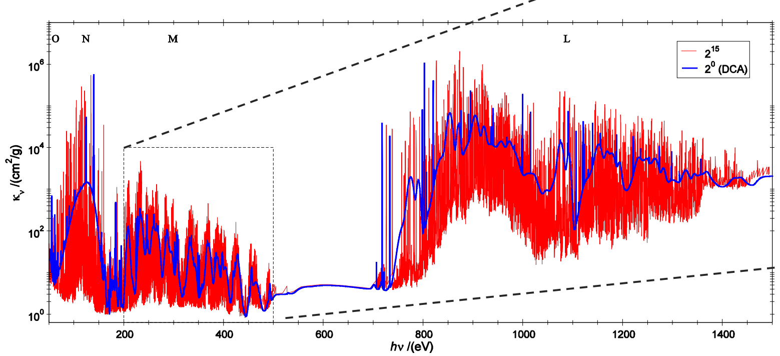
OPAS is a multi-scale atomic code, based on the thermodynamic description of plasma

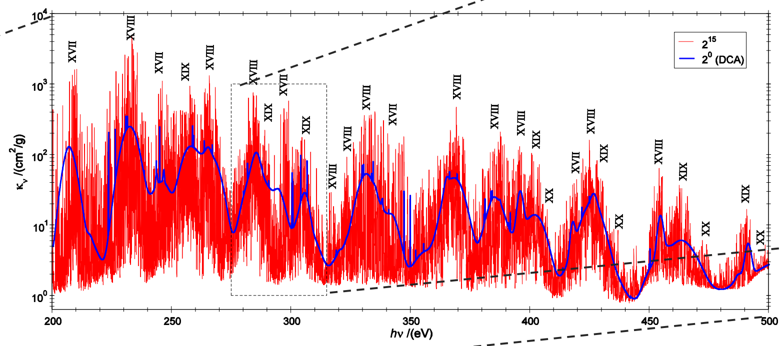
Average Atom	Super-Configurations	Configurations	Atomic Levels	Atomic States

A bound-bound transition arrays can be:

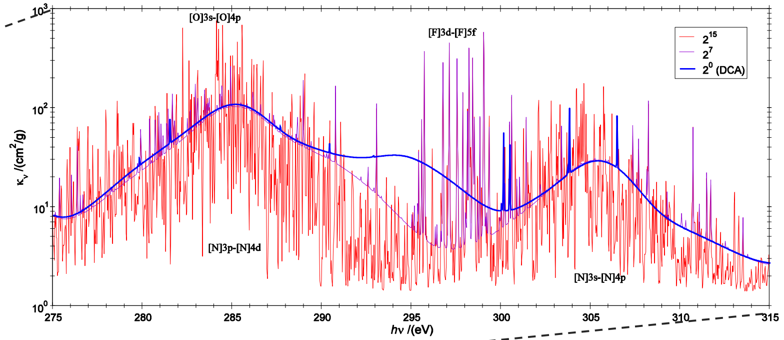
- Unresolved (Bauche's UTA & SOSA)
- Partially resolved (Iglesias PRUTA)
- Resolved (Bruneau's MCDF)

Fe (10^{-4} g/cm^{-3}, 100 eV)





(~10^{12} lines)



Depending on:

- its position ($u \subset [0.2, 13.5] \subset [0.1, 20]$)
- its coalescence level (function of line widths)

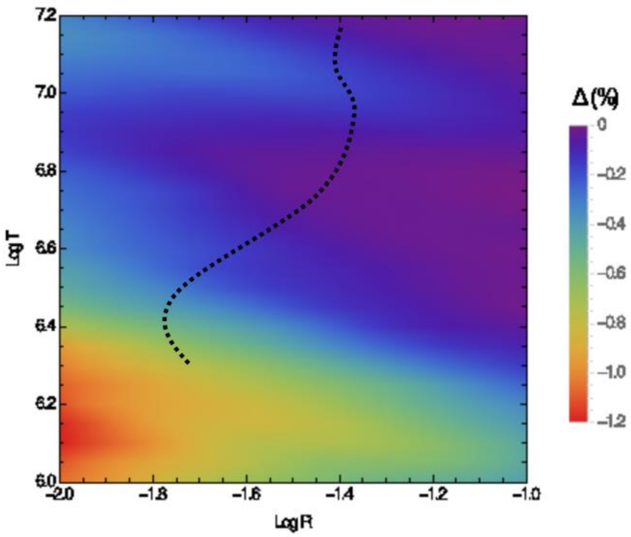
OPAS is a multi-scale atomic code, based on the thermodynamic description of plasma

Average Atom | Super-Configurations | Configurations | Atomic Levels | **Atomic States**

The Stark effect is a line-broadening source...

- The electronic microfield is processed at the quasistatic approximation
- The ionic microfield can be processed exactly, for small, tractable cases :
  - R. W. Lee's LINE2T
  - Ch. Blancard's MCJJ

H-µfield vs mixture-µfield



3. Conclusion and propects

- OPAS had, has and will have implications in stellar modelling
  - The code is rigged for hot plasma opacity productions
    - note: the 2015 tables represent more than year of effort
  - Our collaboration with the Z-machine team is active and on good track
    - the Astrophysicists will be early beneficiaries :)
  - New fruitful collaborations are greatly appreciated!
    - thank you, Gaël!

- OPAS can still evolve...
  - Each new experimental is good to take to test and refine our modules
    - the experimental agreement remains the *juge de paix*
  - We are testing a new Equation-of-State model
    - an alternative approach for the ionic environment

- Non-LTE effects could be evaluated with a cousin code, SAPHyR

Thank you for your attention!

CEA DAM ILE-DE-FRANCE
91297 Arpajon Cedex
France
philippe,cosse@cea.fr
Standard. + 33 1 69 26 40 00